

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE (DD-MM-YYYY) 13-03-2003		2. REPORT TYPE final		3. DATES COVERED (From - To) 01-10-1993 to 31-12-2002	
4. TITLE AND SUBTITLE  Mixed Layer Response to Monssonal Surface Forcing in the Arabian Sea				5a. CONTRACT NUMBER N00014-94-1-0161	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)  Robert A. Weller				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution Woods Hole, MA 02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Regional Office Boston 495 Summer Street Room 627 Boston MA 02210-2109				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT  unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  A surface mooring was deployed in the Arabian Sea for one year. Subsequent analyses provided quantitative descriptions of the upper ocean response to the surface forcing, including heat budgets and identification of the relative roles of various physical processes. One- and three-dimensional models were used to further examine the dynamics of the response at the site of the moored array and to extend the study to the entire Arabian Sea. The fieldwork produced the first long time series of high quality surface meteorology and air-sea fluxes from the Arabian Sea. Observations of the strong cooling heat flux associated with offshore transport gave new insight into the dynamic mechanisms connecting coastal upwelling and upper ocean cooling. New understanding of the physics of the upper ocean in the Arabian Sea was developed, including the impact of the diurnal cycle and of high-frequency wind forcing on the vertical mixing and on larger-scale circulation changes. Comparison of mixed layer model performance suggests some simple improvements in the parameterizations could be made in lieu of resolution of the diurnal cycle.					
15. SUBJECT TERMS  Arabian Sea, air-sea interaction, mixed layer dynamics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)

**DISTRIBUTION STATEMENT A**  
 Approved for Public Release  
 Distribution Unlimited

Standard Form 298 (Rev. 8/98)  
 Prescribed by ANSI Std. Z39.18

321 039

# **Final Report: Mixed Layer Response to Monsoonal Surface Forcing in the Arabi Sea**

Robert A. Weller

Clark 204a MS 29

Woods Hole Oceanographic Institution

Woods Hole, MA 02543

phone: (508) 289-2508 fax: (508) 457-2163 email: [rweller@whoi.edu](mailto:rweller@whoi.edu)

Award Number: N00014-94-1-0161

<http://uop.whoi.edu/>

## **LONG-TERM GOALS**

Our long-range scientific objectives are to observe and understand the temporal and spatial variability of the upper ocean and to identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

## **OBJECTIVES**

Prior to the Arabian Sea Mixed Layer Dynamics Experiment, efforts to observe and understand air-sea interaction and upper ocean variability had never been made in a region characterized by strong, sustained forcing; and the separation of oceanic variability due to atmospheric forcing from that associated with mesoscale variability has been difficult. The combination of strong, sustained monsoonal forcing and mesoscale variability associated with eddies and coastal jets characteristics of the Arabian Sea presented a unique opportunity to add to our understanding of the upper ocean response to atmospheric forcing.

Objectives of the field experiment were to test these ideas: the upper ocean physical and biological responses are largely one-dimensional; Ekman pumping velocities significantly affect the mixed layer evolution; summer mixed layer cooling results from one or a combination of increased cloud cover, large latent heat loss, lateral advection of coastally-upwelled water, open-ocean upwelling, and entrainment; entrainment is dominated by shears associated with sub-inertial wind-driven flow; and mesoscale variability provides the primary source of vertical circulation at the base of the mixed layer. In this continuing effort following the fieldwork, our objective has been to additionally test the following hypotheses: three-dimensional flow divergences due high-frequency and small spatial structure in the wind field are important in the vertical velocity field at the base of the mixed layer, diurnal cycling during the NE monsoon produces a horizontally homogeneous mixed layer, resolution of high frequency wind and diurnal heat forcing significantly modifies the large-scale heat transport, and additional upwelling and vertical mixing associated with the mesoscale contributes significantly to the evolution of the mixed layer.

20030321 039

## **APPROACH**

As part of the ONR-sponsored Arabian Sea Mixed Layer Dynamics experiment we deployed an array of surface and subsurface moorings in cooperation with Rudnick (SIO), Eriksen (UW), Dickey (USC), and Marra (LDEO) from October 1994 to October 1995 at a site just south of the climatological maximum of the Findlater jet in the surface winds in the north-central Arabian Sea (Trask et al., 1995a, b; Ostrom et al., 1996; Baumgartner et al., 1997). The observations showed that there were errors in some widely used flux climatologies, and showed striking differences in the surface forcing between the NE monsoon (November to January), characterized by moderate wind forcing and strong oceanic surface heat and freshwater loss, and the SW monsoon (June-August), with strong winds, significant oceanic heat gain, and reduced evaporation. The mixed layer was observed to cool and deepen during each monsoon, driven primarily by convection during the NE monsoon and wind-driven mixing during the SW monsoon. Mesoscale variability was the major signal in the velocity record, and provided significant horizontal heat fluxes.

Analysis has had two major thrusts. First, quantitative descriptions of the upper ocean response were developed, including heat budgets and identification of the relative roles of various physical processes. Second, one- and three-dimensional models were used to test our understanding of the response at the site of the moored array and to extend it to the entire Arabian Sea.

## **WORK COMPLETED**

This analysis effort followed the fieldwork, which was completed in 1995. The field program provided an unprecedented look at the response of the mixed layer to the wide range of surface forcing found to be associated with the annual cycle in the Arabian Sea (Weller et al., 1998). The effort integrated other data to examine the mesoscale horizontal heat flux and to investigate the effect of the diurnal cycle on the mixed layer in one- and three-dimensional models. This is the final annual report on this project, which had a one-year no cost extension to support completion of the publication of results.

A quantitative analysis of the upper ocean heat budget at the moored array was developed (Fischer, 1997, 2000; Fischer et al., 2002). The ocean variability was documented at the site using the moored data (Weller et al., 2002). Additional data sets of combined TOPEX/ERS altimetry (courtesy of Leben and Fox, CCAR), satellite SST (JPL), and SeaSoar surveys (Brink, WHOI; Lee, UW APL) have allowed identification of the dynamic origins of the strong horizontal heat fluxes found at the site (Fischer, 2000; Fischer et al. 2002). A collaboration with Craig Lee used climatological data supplied in part by Simon Josey (SOC) to examine the relative effects of Ekman pumping and locally driven entrainment on the deepening of the mixed layer across the Arabian Sea (Lee et al., 2000).

The three-dimensional model of McCreary was used to investigate the Arabian Sea response to diurnal variability in the solar heat flux and to high frequency and high spatial variability in the wind stress forcing. The collaboration with Jay McCreary (UH/IPRC) also included model/data comparisons and cooperation on studies of the effect of the diurnal cycle in a coupled physical-biological model (McCreary et al., 2001). To further examine how the diurnal cycle affects the vertical mixing and redistribution of heat, the responses of a number of one-dimensional mixed layer models were examined under a variety of surface forcing conditions.

## RESULTS

The field experiment captured the first yearlong high quality surface flux and upper ocean record in the Arabian Sea. The process that supported the strong horizontal advection of water during the SW monsoon seen in the heat budget of the moored array was identified using satellite SST imagery and altimetry as the advection of water upwelled at the Omani coast and subsequent transport of it well offshore by a filament. During the NE monsoon, strong horizontal heat advection at the moored array was found to be associated with mesoscale eddies that had been generated in the previous SW monsoon and then propagated westward. The altimetric record shows that mesoscale activity is elevated along the Arabian coast during the SW monsoon, suggesting that these coastal filaments play an important role in the offshore transport and mixing of coastally upwelled water.

The SST and mixed layer depth were observed to respond to high frequency (diurnal to atmospheric synoptic time scales) variability in the surface heat flux and wind stress. The rectified effect of this high frequency forcing was investigated using the McCreary three-dimensional reduced gravity thermodynamic model of the Arabian Sea and Indian Ocean. Both the diurnal cycle and high frequency wind forcing acted locally to increase vertical mixing in the model, reducing the SST. Interactions between the local response to the surface forcing, Ekman divergences, and remotely propagated signals in the model can reverse this, particularly at low latitudes. The annual mean SST, however, is lowered under both diurnal heat and high frequency wind forcing, changing the balance between the net surface heat flux (which is dependent in turn on the SST) and the meridional heat flux in the model.

The additional vertical mixing caused by a resolved wind stress field has been studied before and can be understood simply based on the energy balance. The net effect of the diurnal cycle on SST and MLD has not been studied systematically, and cannot be understood as simply. The rectification of the diurnal cycle was explored across a wide parameter space in net heat and wind forcing using several one-dimensional upper ocean models with different representations of vertical mixing processes. All show increased vertical mixing in response to the diurnal cycle in net heating conditions, but the degree of enhanced mixing is highly dependent on the model formulation used.

## IMPACT FOR SCIENCE

The fieldwork produced the first long time series of high quality surface meteorology and air-sea fluxes to be obtained in the Arabian Sea. This data provides a means to guide the selection of forcing products for ocean models forcing products for ocean models to be used for research and operations. Observations of the strong cooling heat flux associated with offshore transport give insight into the dynamic mechanisms connecting coastal upwelling and upper ocean cooling. Similarly, the new understanding of the physics of the upper ocean in the Arabian Sea will influence future studies and operational modeling. The net effect of the diurnal cycle and the importance of high-frequency wind forcing on the vertical mixing of temperature and on larger-scale circulation changes will be applicable to any modeling study of upper ocean circulation or biology, particularly in regions where mixed-layer diurnal variability is important. The comparison of mixed layer models suggests some simple improvements in the parameterizations could be made in lieu of resolution of the diurnal cycle.

## RELATIONSHIPS TO OTHER PROGRAMS

Cooperation with Kindle (NRL) in modeling should lead to improvement of Navy ocean forecast models in the region and has led to confirmation of the quality of FNMOC winds in the region (Rochford et al, 2000).

This effort included close collaborations with other efforts: numerical modeling (McCreary, UH/IPRC; Kindle, NRL), satellite remote sensing (Leben and Fox, CCAR; Arnone, NRL; Halpern, JPL)(Halpern et al., 1998), and with the other ONR Arabian Sea investigators (Lee, Brink, Eriksen, Rudnick, Dickey, Marra). The role of mesoscale eddies in pulses in productivity has been investigated with these investigators (Marra et al., 1998; Dickey et al., 1998; Wiggert et al., 2000; Kinkade et al., 2000) and also with Honjo (WHOI), Prell (Brown), and Dymond (OSU).

## REFERENCES

- Trask, R. P., B.S. Way, W. M. Ostrom, G.P. Allsup, and R. A. Weller, 1995a. Arabian Sea mixed layer dynamics experiment: mooring cruise report R/V Thomas Thompson Cruise number 40 11 October-25 October, 1995. Upper Ocean Processes Group Technical Report 95-1, Woods Hole Oceanographic Institution, Woods Hole, MA, USA 02543, 64 pp.
- Trask, R. P., R. A. Weller, W. M. Ostrom, 1995b. Arabian Sea mixed layer dynamics experiment: mooring cruise report R/V Thomas Thompson Cruise number 46 14 April-29 April, 1995. Upper Ocean Processes Group Technical Report 95-14, Woods Hole Oceanographic Institution, Woods Hole, MA, USA 02543, 92 pp.
- Ostrom, W. B., B.S. Way, R.A. Weller, J.D. Ware, and R. P. Trask, 1996. Arabian Sea mixed layer dynamics experiment: mooring cruise report R/V Thomas Thompson Cruise number 52 14 October -25 October 1995. Upper Ocean Processes Group Technical Report 96-2, Woods Hole Oceanographic Institution, Woods Hole, MA USA 02543.
- Baumgartner, M. F., N. J. Brink, W. M. Ostrom, R. P. Trask, and R. A. Weller, 1997. Arabian Sea mixed layer dynamics experiment data report mooring cruise report. Upper Ocean Processes Group Technical Report 97-13, Woods Hole Oceanographic Institution, Woods Hole, MA, USA 02543, 169 pp.
- Fischer, A.S., 1997. Arabian Sea mixed layer deepening during the monsoon: observations and dynamics. S. M. thesis, MIT/WHOI Joint Program in Oceanography, Woods Hole, MA.
- Weller, R. A., M. F. Baumgartner, S. A. Josey, A. S. Fischer, and J. C. Kindle, 1998. Atmospheric forcing in the Arabian Sea during 1994-1995: observations and comparisons with climatology and models. *Deep-Sea Research II*, **45**, 1961-1999.
- Marra, J., T. D. Dickey, C. Ho, C. S. Kinkade, D. Sigurdson, R. Weller, and R. T. Barber, 1998. Variability in primary production as observed from moored observations in the central Arabian Sea in 1995. *Deep-Sea Research II*, **45**, 2253-2268.



- Dickey, T., J. Marra, D. E. Sigurdson, R.A. Weller, C. S. Kinkade, S. E. Zedler, J. D. Wiggert, and C. Langdon, 1998. Seasonal variability of bio-optical and physical properties in the Arabian Sea: October 1994-1995. *Deep-Sea Research II*, **45**, 2001-2025.
- Halpern, D., M. H. Freilich, and R. A. Weller, 1998. Arabian sea surface winds and ocean transports determined from ERS-1 scatterometer, *Journal of Geophysical Research*, **103**, 7799-7805.
- Fischer, A. S., 2000. The upper ocean response to the monsoon in the Arabian Sea, Ph. D. thesis, MIT/WHOI Joint program in Oceanography, Woods Hole, MA, 2000.
- Wiggert, J., B. H. Jones, T. D. Dickey, K. Brink, R. A. Weller, J. Marra, and L. Codispoti, 2000. The northeast monsoon's impact on mixing, phytoplankton biomass and nutrient cycling in the Arabian Sea. *Deep-Sea Research II*, **47**, 1353-1385.
- Rochford, P. A., J. C. Kindle, P. C. Gallacher, and R.A. Weller, 2000. Sensitivity of the Arabian Sea mixed layer to the 1994-95 operational wind products. *Journal of Geophysical Research*, **105**, 14141-14362.
- Lee, C.M., B. H. Jones, K. H. Brink, and A.S. Fischer, 2000. The upper-ocean response to monsoonal forcing in the Arabian Sea: seasonal and spatial variability. *Deep-Sea Research II*, **47**, 1177-1226.
- Kinkade, C. S., J. Marra, T. D. Dickey, C. Langdon, D. E. Sigurdson, and R. Weller, 2000. Diel bio-optical variability observed from moored sensors in the Arabian Sea. *Deep-Sea Research II*, **46**, 1813-1831.
- McCreary, J. P., Jr., K. E. Kohler, R. R. Hood, S. Smith, J. Kindle, A. Fischer, and R. A. Weller, 2001. Influences of diurnal and intraseasonal forcing on mixed-layer and biological variability in the Central Arabian Sea, *Journal of Geophysical Research*, **106**, 7139-7155.
- Weller, R. A., A. S. Fischer, D. L. Rudnick, C. C. Eriksen, T. D. Dickey, J. Marra, C. Fox, and R. Leben, 2002. Moored observations of upper-ocean response to the monsoons in the Arabian Sea during 1994-1995. *Deep-Sea Research II*, **49**, 2195-2230.
- Fischer, A. S., R. A. Weller, D. L. Rudnick, C. C. Eriksen, C. M. Lee, K. H. Brink, C. A. Fox, and R. R. Leben, 2002. Mesoscale eddies, coastal upwelling, and the upper-ocean heat in the Arabian Sea. *Deep-Sea Research II*, **49**, 2231-2264.